

DEVELOPMENT OF A GENERIC CREEP-FATIGUE LIFE PREDICTION MODEL

Tarun Goswami (Principal Investigator)
Associate Professor of Mechanical Engineering
Arkansas Tech Univeristy, Russellville AR 72801

EXECUTIVE SUMMARY

The objective of this research proposal is to further compile creep-fatigue data of steel alloys and superalloys used in military aircraft engines and/or rocket engines and to develop a statistical multivariate equation. The newly derived model will be a probabilistic fit to all the data compiled from various sources. Attempts will be made to procure the creep-fatigue data from NASA Glenn Research Center and other sources to further develop life prediction models for specific alloy groups. In a previous effort [1-3], a bank of creep-fatigue data has been compiled and tabulated under a range of known test parameters. These test parameters are called independent variables, namely; total strain range, strain rate, hold time, and temperature. The present research attempts to use these variables to develop a multivariate equation, which will be a probabilistic equation fitting a large database. The data predicted by the new model will be analyzed using the normal distribution fits, the closer the predicted lives are with the experimental lives (normal line 1 to 1 fit) the better the prediction. This will be evaluated in terms of a coefficient of correlation, R^2 as well. A multivariate equation developed earlier [3] has the following form, where S, R, T, and H have specific meaning discussed later.

$$\begin{aligned} \text{Log } N_f = & 8.6359 - 13.792 S + 11.414 RA - 0.0161 T + 0.0001 H + 25.224 \log S \\ & + 24.931 \log H - 5.7788 \ln RA - 0.0127 \ln T - 0.0246 \ln H + 11.592 S^2 - 4.4784 R^2 \\ & - 12.271 H^2 - 2.2972 S^4 + 0.6938 R^4 + 0.9505 H^4 - 4.1866 SR + 1.3506 SR^2 \\ & - 4.9318 S^2R - 0.0435 S^2R^4 + 0.883 S^4R + 0.0925 S^4R^2 + 0.0006 S^4R^4 - 6.2141 ST \\ & + 0.1932 ST^2 - 3.6614 S^2T + 0.1218 S^2T^2 + 0.7672 S^4T - 0.0342 S^4T^2 - 9.1907 SH \\ & + 3.4604 SH^2 - 3.4025 S^2H + 0.9517 S^2H^2 + 0.1798 S^2H^4 - 0.0548 S^4H - 0.0064 S^4H^4 \\ & + 2.1396 RT - 0.1137 RT^2 + 881E^{-8} RT^4 + 0.8492 R^2T - 0.0381 R^2T^2 - 0.0747 R^4T \\ & + 0.0022 R^4T^2 + 37.899 RH - 16.111 RH^2 + 0.5362 RH^4 + 12.652 R^2H - 4.5123 R^2H^2 \\ & + 0.0176 R^2H^4 - 0.5045 R^4H + 0.0094 R^4H^4 + 0.3358 TH - 0.2157 TH^2 - 0.0195 TH^4 \\ & - 0.0311 T^2H + 0.022 T^2H^2 - 0.0014 T^2H^4 - 0.9112 S^5 + 0.2048 R^5 - 0.1325 H^5 \\ & - 0.0871 S^6 + 0.0174 R^6 + 0.0155 H^6 + 0.1316 S^5R - 0.0003 S^5R^5 - 303E^{-7} S^5R^6 \\ & + 0.0102 S^6R - 172E^{-7} S^6R^5 - 187E^{-8} S^6R^6 + 0.262 S^5T - 0.013 S^5T^2 - 401E^{-8} S^5T^4 \\ & + 0.0249 S^6T - 0.0012 S^6T^2 - 18E^{-7} S^6T^4 - 0.163 S^5H + 0.021 S^5H^4 - 0.0057 S^5H^5 \\ & + 519E^{-7} S^5H^6 - 0.0381 S^6H + 0.0007 S^6H^2 + 0.0052 S^6H^4 - 0.0013 S^6H^5 \\ & + 0.0351 R^5S - 0.0049 R^5S^2 + 0.0049 R^6S - 0.0166 R^5T + 0.0003 R^5T^2 - 41E^{-9} R^5T^4 \\ & + 24E^{-11} R^5T^5 - 0.0011 R^6T + 123E^{-7} R^6T^2 - 0.0201 R^5H - 0.0538 R^5H^2 \\ & + 0.0017 R^5H^4 + 0.001 R^5H^5 + 0.0061 R^6H - 0.0077 R^6H^2 + 0.0001 R^6H^5 \\ & + 476E^{-8} R^6H^6 - 28E^{-14} T^6H^5 + 0.1442 H^5S - 0.0376 H^6S - 0.01 H^6S^2 + 0.0422 H^5R^2 \\ & + 0.0106 H^6R - 0.0012 H^6R^2 + 0.0204 H^5T - 0.0032 H^6T + 14E^{-9} H^6T^4 \end{aligned}$$

This proposed research will develop a new model for nickel-based superalloys.

INTRODUCTION

The components of gas turbine engines and rocket motors operate under very aggressive environments and high mechanical and thermal stresses, where creep and fatigue interact. As a result, failure of such components as turbine disks and blades in these applications occurs by low cycle fatigue mechanisms. Therefore, creep-fatigue life prediction studies are very important in the design of such components. The material of construction in these applications is a number of steel alloys and superalloys. Previous work covers the low cycle fatigue life prediction of low alloy steels, stainless steels, titanium alloys and superalloys using phenomenological approaches and statistical (probabilistic) models [1-3]. The Principal Investigator is known at Glenn Research Center, has visited twice in the last 10 years, and presented his results. This proposal will bring the two Institutions (Glenn Research Center and Arkansas Tech Univeristy) in a formal working relation, where the knowledge generated from this research project will be included in undergraduate and/or graduate curriculum and help NASA predict a particular material behavior using the models developed in this project.

METHODOLOGY

In an earlier effort [1-3] the following materials were studied, 1) pure metals, 2) solder alloys, 3) Copper alloys, 4) low alloy steels, 5) stainless steels, 6) titanium alloys, 7) tantalum alloys, 8) superalloys and superalloys produced by mechanical alloying and/or single crystal processes. The proposed research will isolate the creep-fatigue data on superalloys from [3] and further expand the database by adding new data procured from GRC. These data will be used to develop a new life prediction equation within the lines of research presented in [1-3].

A number of software packages will be used to derive the multivariate equation. The Statistical Analysis System (SAS) uses a stepwise and maximum R^2 improvement procedure by selecting independent variables or specified combinations of transformed independent variables until the best model was obtained. Transformations to independent variables will be made as follows:

$$S = \text{Log}_{10}(\Delta\epsilon_r / 100)$$

$$R = \text{Log}_{10}(\dot{\epsilon})$$

$$T = T_c / 100$$

$$H = \text{Log}_{10}(t_h + 1)$$

These transformations are for total strain range ($\Delta\epsilon_f$), strain rate ($\dot{\epsilon}$), temperature (T_c), and hold time (t_h), respectively, were chosen for two reasons:

1. they resulted in a decrease in the number of terms required in modeling, and,
2. the transformed variables all have absolute values in the range of 0 to 10, thus, producing residuals in predicted and experimental values within a small band.

A typical residual plot is shown in Fig. 1 and a normal distribution plot in the predicted versus residual life values are presented in Fig. 2.

A generic model derived for metals, by fitting nearly 2100 data points, has the following form:

$$\begin{aligned} \text{Log } N_f = & 8.6359 - 13.792 S + 11.414 RA - 0.0161 T + 0.0001 H + 25.224 \log S \\ & + 24.931 \log H - 5.7788 \ln RA - 0.0127 \ln T - 0.0246 \ln H + 11.592 S^2 - 4.4784 R^2 \\ & - 12.271 H^2 - 2.2972 S^4 + 0.6938 R^4 + 0.9505 H^4 - 4.1866 SR + 1.3506 SR^2 \\ & - 4.9318 S^2R - 0.0435 S^2R^4 + 0.883 S^4R + 0.0925 S^4R^2 + 0.0006 S^4R^4 - 6.2141 ST \\ & + 0.1932 ST^2 - 3.6614 S^2T + 0.1218 S^2T^2 + 0.7672 S^4T - 0.0342 S^4T^2 - 9.1907 SH \\ & + 3.4604 SH^2 - 3.4025 S^2H + 0.9517 S^2H^2 + 0.1798 S^2H^4 - 0.0548 S^4H - 0.0064 S^4H^4 \\ & + 2.1396 RT - 0.1137 RT^2 + 881E^{-8} RT^4 + 0.8492 R^2T - 0.0381 R^2T^2 - 0.0747 R^4T \\ & + 0.0022 R^4T^2 + 37.899 RH - 16.111 RH^2 + 0.5362 RH^4 + 12.652 R^2H - 4.5123 R^2H^2 \\ & + 0.0176 R^2H^4 - 0.5045 R^4H + 0.0094 R^4H^4 + 0.3358 TH - 0.2157 TH^2 - 0.0195 TH^4 \\ & - 0.0311 T^2H + 0.022 T^2H^2 - 0.0014 T^2H^4 - 0.9112 S^5 + 0.2048 R^5 - 0.1325 H^5 \\ & - 0.0871 S^6 + 0.0174 R^6 + 0.0155 H^6 + 0.1316 S^5R - 0.0003 S^5R^5 - 303E^{-7} S^5R^6 \\ & + 0.0102 S^6R - 172E^{-7} S^6R^5 - 187E^{-8} S^6R^6 + 0.262 S^5T - 0.013 S^5T^2 - 401E^{-8} S^5T^4 \\ & + 0.0249 S^6T - 0.0012 S^6T^2 - 18E^{-7} S^6T^4 - 0.163 S^5H + 0.021 S^5H^4 - 0.0057 S^5H^5 \\ & + 519E^{-7} S^5H^6 - 0.0381 S^6H + 0.0007 S^6H^2 + 0.0052 S^6H^4 - 0.0013 S^6H^5 \\ & + 0.0351 R^5S - 0.0049 R^5S^2 + 0.0049 R^6S - 0.0166 R^5T + 0.0003 R^5T^2 - 41E^{-9} R^5T^4 \\ & + 24E^{-11} R^5T^5 - 0.0011 R^6T + 123E^{-7} R^6T^2 - 0.0201 R^5H - 0.0538 R^5H^2 \\ & + 0.0017 R^5H^4 + 0.001 R^5H^5 + 0.0061 R^6H - 0.0077 R^6H^2 + 0.0001 R^6H^5 \\ & + 476E^{-8} R^6H^6 - 28E^{-14} T^6H^5 + 0.1442 H^5S - 0.0376 H^6S - 0.01 H^6S^2 + 0.0422 H^5R^2 \\ & + 0.0106 H^6R - 0.0012 H^6R^2 + 0.0204 H^5T - 0.0032 H^6T + 14E^{-9} H^6T^4 \end{aligned}$$

The above equation is a generic life prediction model. However, this equation is not a representative equation to predict the creep-fatigue life of superalloys. Therefore, the proposed research will isolate the creep-fatigue data on superalloys and add more data to database to develop a dedicated model to predict creep-fatigue life of superalloys. The new model will be useful to NASA to determine the trends in the creep-fatigue behavior of new materials that have not been tested to evaluate the applicability of new materials. Once the applicability of this proposal has been proven, new data will be obtained from GRC to fully the develop the model to plan the testing program and predict the life.

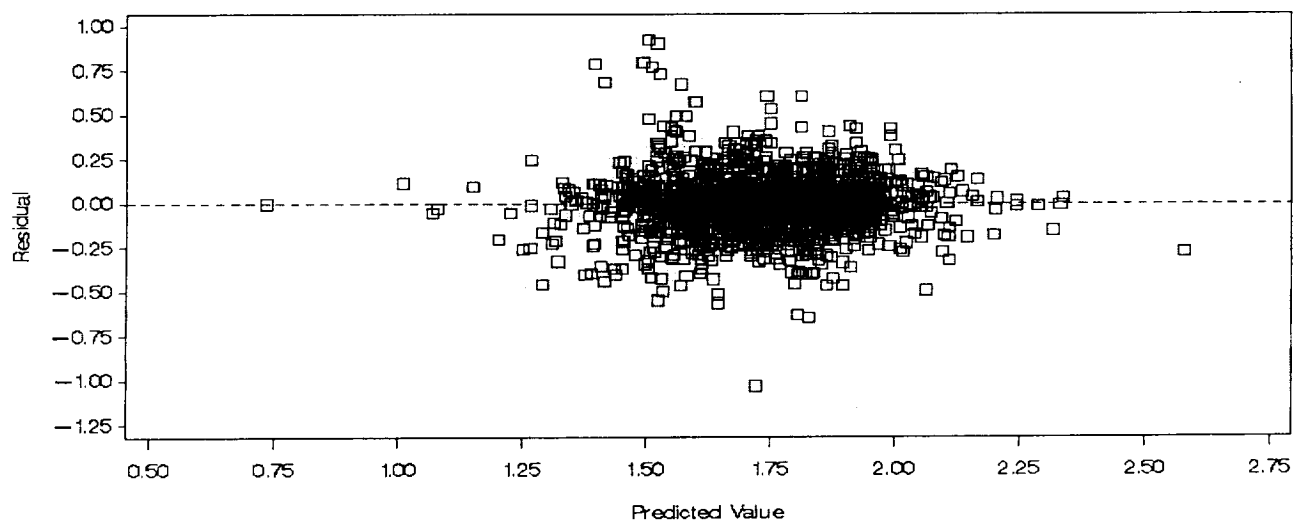


Fig. 1. Residual data and predicted cycles to failure

A normal probability plot has been presented below.

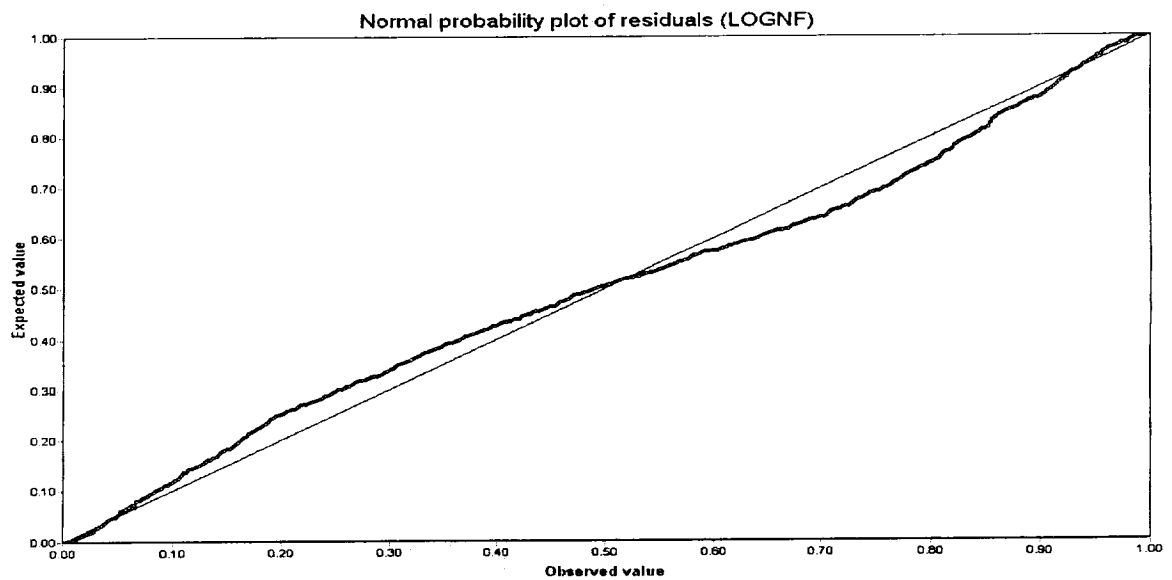


Fig. 2. Normal probability distribution of the experimental and predicted cycles to failure.